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Next-to-leading Corrections to the Higgs Boson Transverse Momentum Spectrum in Gluon Fusion

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We present a fully analytic calculation of the Higgs boson transverse momentum and rapidity distributions, for nonzero Higgs $p_\perp$, at next-to-leading order in the infinite-top-mass approximation. We separate the cross section into a part that contains the dominant soft, virtual, collinear, and small-$p_\perp$-enhanced contributions, and the remainder, which is organized by the contributions due to different parton helicities. We use this cross section to investigate analytically the small-$p_\perp$ limit and compare with the expectation from the resummation of large logarithms of the type $\ln m_H/p_\perp$. We also compute numerically the cross section at moderate $p_\perp$ where a fixed-order calculation is reliable. We find a K-factor that varies from $\approx 1.6-1.8$, and a reduction in the scale dependence, as compared to leading order. Our analysis suggests that the contribution of current parton distributions to the total uncertainty on this cross section at the LHC is probably less than that due to uncalculated higher orders.

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Introduction

Our current understanding of particle physics depends crucially on the breaking of the electroweak symmetry to give masses to the $W^\pm$ and Z bosons, as well as to all of the matter particles. Yet, despite decades of extremely precise and successful predictions, the exact mechanism by which this symmetry breaking occurs is not known. The simplest model involves a single weak $SU(2)$ scalar doublet which has a nonzero vacuum expectation value. After rewriting in terms of the physical states, this "standard model" leaves behind a single neutral scalar, the Higgs boson, as its signature Higgs. Furthermore, models with extended Higgs sectors, including the minimal supersymmetric standard model (MSSM), often have a relatively light scalar with properties similar to the standard model Higgs boson. Therefore, the Higgs boson is at the top of any list of new particles to be found.

The direct search for the standard model Higgs boson in the $e^+e^- \to HZ$ channel at LEP2 has put a lower bound on its mass of 114.1 GeV LEP2Limit. Moreover, there are hints of a signal in the data just above this bound. Meanwhile, precision electroweak measurements give an upper limit of $m_H 196-230$ GeV at the 95% confidence level HiggsRadCorr. Therefore, if a standard model Higgs boson exists, its allowed mass range is not large. Run II of the Tevatron can exclude a standard model Higgs boson over much of this mass range, up to about 180 GeV, assuming 15 fb^{-1} per experiment. However, a definitive 5σ discovery is difficult to obtain at this luminosity RunIIExpectations for a mass much beyond the LEP2 limit. The Large Hadron Collider (LHC) at CERN will be needed to certify a Higgs discovery, and to pin down its mass and couplings.

The dominant production mechanism for the Higgs boson at the LHC is the gluon-gluon fusion process. This process occurs at leading order (LO), $\mathcal{O}(\alpha_s^2)$, through a heavy quark loop. As is typical in Quantum Chromodynamic (QCD) processes initiated by gluons, the radiative corrections are quite large. The next-to-leading order (NLO) corrections have been computed, including the full top-mass dependence zerwas, and indeed, the K-factor is $\approx 1.4-2.2$, depending on the Higgs mass and the scale choice. The computation with full m_t-dependence requires the calculation of two-loop diagrams and is quite complex. Luckily, it simplifies greatly in the limit of large top quark mass ($m_t \to \infty$). In this limit, one can integrate out the top quark loop, leaving behind an effective gauge-invariant Hgg vertex HggVertex. The Higgs boson production cross section has been calculated at NLO in this limit in Refs. Dawson. It gives an excellent approximation to the full m_t-dependent NLO cross section for $m_H 2m_t$. Furthermore, the K-factor calculated in the effective theory gives a good approximation to the full m_t-dependent K-factor, even for larger Higgs masses. Attempts have been made to estimate the NNLO corrections using soft-gluon approximations CdFG and resummations Kramer. Recently the full NNLO cross section in the large-m_t limit has been computed HK. Although the K factor is larger still at NNLO, the increase is not as severe as the NLO enhancement, and the perturbation series seems to be well-behaved.

In addition to increasing the total cross section, the QCD radiation can have a large effect on the kinematic distributions of the Higgs boson. Most notably, the transverse momentum, $p_\perp$, of the Higgs boson is exactly zero at LO, but is typically nonzero at higher orders, due to additional radiated partons. In fact, this additional QCD radiation has led some to consider searching for the Higgs boson in association with a tagged jet at the LHC Dubinin. Regardless of whether additional jets are tagged in the Higgs events, it is useful to understand the transverse momentum distributions of both the Higgs signal and the background. The transverse momentum spectrum of the Higgs boson has been calculated at LONote that the LO contribution to the $p_\perp$ spectrum at non-zero $p_\perp$ is actually down by α_s compared to the LO cross section; it contributes to the cross section at NLO. both with the full top quark mass dependence and in the large-m_t limit EHSvdB. It was seen that the large-m_t limit is a good approximation to this distribution if $m_H 2m_t$ and $p_\perp m_t$. Recently, it was shown DelDuca that these conditions are also sufficient to use the large-m_t limit for Higgs +2 jet production; *i.e,* the transverse momenta of the Higgs boson and the jets must be less than $\approx m_t$, but other invariants such as the total partonic center-of-mass energy can still be large.

In this work we calculate the NLO corrections in the large-m_t limit to the Higgs boson $p_\perp$ and rapidity spectrum, $d\sigma/dp_\perp^2/dy_H$, at the LHC. Initial results of our calculation, which included the purely gluonic contributions, were reported in Ref. chris. The NLO corrections in this limit have been calculated previously in Ref. dFGK, using a Monte Carlo integration to do the phase space integrations, after cancellation of the infrared singularities. More recently, a full analytic calculation of the $p_\perp$ spectrum was presented in Ref. RSvN. Our calculation is similar to that in RSvN in that it is completely analytic. However, by treating the contributions of different helicity configurations separately, we are able to report the full formulae for the differential cross section in this paper, in a relatively tractable form. Another difference is that we have used the +function technique to deal with soft singularities, whereas an artificial parameter was introduced in RSvN to separate the soft and hard radiative contributions. Our technique allows more of the universal structure of the NLO corrections to be apparent. Finally, since much of the total Higgs cross section occurs at not-too-large $p_\perp$, we investigate the low $p_\perp$ limit of our result.

At small Higgs transverse momenta the perturbation series for the $p_\perp$ spectrum becomes unstable, containing terms like $(\alpha_s^2/p_\perp^2)\alpha_s^n \ln^m(m_H^2/p_\perp^2)$, with the leading logarithm occurring for $m = 2n-1$. This logarithmic series has been resummed, using the techniques of Collins, Soper, and Sterman CSS, at various levels of approximation Hresum. The NLO differential cross section at small $p_\perp$ contains the fixed order terms in the logarithmic expansion corresponding to $n = 2,\ m = 3, 2, 1, 0$. In particular, the so-called $B^{(2)}$ coefficient in the logarithmic series occurs in our calculation at $n = 2,\ m = 0$. This coefficient has recently been derived dFG using the universality of the real emission contributions, combined with knowledge of the virtual correction amplitudes in the soft and collinear limits. Using our analytic expressions for the NLO $p_\perp$ spectrum, we have verified this coefficient by direct calculation. The analytic comparison of our cross section in the small-$p_\perp$ limit with that expected from the resummation formulae is a very stringent check on our results.

The remainder of this paper is organized as follows. In section sec:LO we set up the calculation by defining some general formulae and giving the Born level expressions for the differential $p_\perp$ and rapidity spectrum. In section sec:NLO we obtain the $\mathcal{O}(\alpha_s)$ corrections to this by combining the virtual one-loop (in the effective large-m_t theory) amplitudes with the tree-level real radiative corrections. Although both of these contributions are infrared divergent, these divergences cancel after they are added together, using $\overline{\mathrm{MS}}$ parton density functions, defined at NLO. In the main text we give formulae for the largest contribution to the distribution, which contains all terms having singular behavior as one of the real QCD partons becomes soft or collinear, as well as most of the terms that are leading at small-$p_\perp$ (all but the $m = 0$ terms from the previous paragraph). For lack of a better word, we label these contributions the "singular" contributions. The remaining "nonsingular" contributions are given in appendix app:nsrc. In section sec:numbers we give some numerical results and analysis obtained from our calculation, showing some representative distributions at the LHC. We also comment on the numerical comparison of our results to previous calculations. In section sec:smallpt we consider the small-$p_\perp$ limit of our result, and compute directly the $B^{(2)}$ coefficient. Finally, in section sec:conclusions we give our conclusions.

Higgs $p_\perp$ Spectrum: General Formulae and Leading Order expressions sec:LO

In the large-m_t limit the top quark can be removed from the full theory, leaving a residual Higgs-gluon

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ross section at NLO. ,

coupling term in the lagrangian of the effective theory: equation $\mathrm{L}_{\mathrm{eff}} \; = \; -\frac{1}{4}\left[1-\frac{\alpha_s}{3\pi}\frac{H}{v}\left(1+\frac{\alpha_s}{4\pi}\Delta\right)\right] G^a_{\mu\nu}G^{a\mu\nu}$.